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SUBJECT: Polarization Measurements on   DATE: March 28, 1969
          Stellar X-ray Sources - Case 630

                                                FROM: F. F. Tomblin

                          ABSTRACT

          X-ray polarization experiments should be conducted on
unmanned satellites in the near future to determine the need
for more sophisticated systems on advanced manned ATM missions.
Unmanned experiments could be performed simply with little more
expense than conventional x-ray astronomy sky survey experi-
ments. They would provide data on the existence of polarized
sources and indicate which sources should be studied in detail
later by a more elaborate manned system. Polarization informa-
tion will be useful in determining the nature of stellar x-ray
emission mechanisms. Synchrotron emission is the most likely
mechanism for producing polarized x-rays.

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MEMORANDUM FOR FILE

I.   INTRODUCTION

Considerable theoretical effort has been made to establish the presence of polarized stellar x-ray sources, yet no conclusive experiments have been performed to establish the existence of such sources. Novick has proposed a polarimeter similar to the one described here for flight on an advanced ATM mission.[1] He is also conducting balloon flights. No results are available as yet.

This note outlines the difficulties involved in such a measurement and proposes how experiments could be performed in both the manned and unmanned space programs. First, it is worthwhile to summarize briefly the emission processes which may be responsible polarization of x-ray sources.

Any mechanism which accelerates electrons will generate photons. Two such effects are likely methods of generating polarized radiation in stellar sources. One is synchrotron radiation which is emitted by an electron moving in a magnetic field. The other is bremsstrahlung radiated from collisions of thermal electrons in a hot plasma.

The inverse Compton effect is another possible source of high energy photons in diffuse gases. It is the result of optical photons scattering with high energy electrons. The electrons impart energy to the photon by a process which is the inverse of normal Compton scattering.

These three effects underlie the basic theories of x-ray production from various types of stellar sources. Of the three, only synchrotron radiation may produce highly polarized x-rays. Bremsstrahlung may be responsible for partially polarized x-rays from electrons moving in primarily one direction. Partial polarization may also appear from synchrotron emission where the magnetic field shows large scale irregularities.[2]

Optical photons are sometimes polarized by scattering from clouds of aligned grains. If such photons were transformed to x-ray energies by inverse Compton scattering from energetic electrons, the x-rays would also be polarized. However, estimates indicate that this effect would not produce polarization in excess of 0.05%.[2]

The emission mechanism of many x-ray sources remains uncertain. Additional information which could be obtained from polarization measurements would be quite beneficial. For sources such as the Crab Nebula, CasA, and M87, where synchrotron radiation is the most probable source of radiation, the degree of polarization would give some information on the nature of magnetic fields creating the synchrotron radiation.

II. EXPERIMENTAL DESIGN

The Compton effect may be used to determine the polarization of an x-ray by looking at the scattered beam at 90° from the incident direction.

The differential Compton scattering cross section may be written as

$$\frac{d\sigma}{d\Omega} = \left(\frac{e^2}{mc^2}\right)^2 \cos^2\theta \text{ for } E << 0.5\text{MeV at } 90° \text{ from the incident beam,} \quad (3)$$

where θ is the angle between the incident photon electric vector and the scattered photon electric vector as shown in Figure 1, and $\frac{d\sigma}{d\Omega}$ is the cross section per unit solid angle. If the incident radiation is totally plane polarized then there should be no scattering of photons with electric vectors at $\theta = 90°$, and maximum scattering at $\theta = 0°$.

Such a Compton polarimeter has been used to determine the polarization of gamma radiation in connection with angular correlation experiments.[4] The use of this technique is limited to the region of the x-ray spectrum where the Compton effect is dominant over other processes such as the photoelectric effect and pair production. Since most x-ray astronomy experiments are conducted at energies below 50 KeV, one must design experiments to minimize photoelectric absorption at low energies.

The lower limit may be reduced by judicious selection of the scattering material. For example, in aluminum the photoelectric effect and Compton effect have identical cross sections at 50 KeV. Below this point the photoelectric absorption dominates. To lower this crossover point a lower Z material must

be used. Figure 2 shows the mean free path for Compton scattering and photoelectric effect for various materials as a function of energy. It is clear that there is an advantage in using materials with the smallest atomic number possible. For example, crossover points are 11 KeV and 3.3 KeV for Lithium Hydride and Liquid Hydrogen, respectively.

The optimum geometry is such that the path length of the photon before scattering must be of the order of a Compton mean free path. The scattered photons at 90° to the incident direction should then travel through the least amount of material to a detector. This configuration is shown in Figure 3.

The efficiency of such a polarization detector is restricted because only a small fraction of the incident radiation is detected. For example, assume that one has an incident beam of plane polarized x-rays. For 3.3 KeV photons incident on a liquid hydrogen scatterer, only 50% of the x-rays will be Compton scattered, and the remainder will be absorbed by the photoelectric effect. Of those which are Compton scattered approximately 30% suffer photo absorption or a second Compton scattering. (This depends on the thickness of the scattering cylinder.) However, only about 6% of the total scattered x-radiation is ejected at 90°±10° and passes through the collimation in front of the detectors. Thus only about 2% of the initial radiation reaches the detector. This fraction must be divided among at least 8 different detector groups (see Figure 3) to determine the polarization. In practice the detector would be calibrated with an unpolarized source to correct for any irregularity or differences in detector efficiency.

III. A COLLIMATED POLARIMETER

If the polarimeter is collimated and used as a "telescope", the effective area of the polarimeter is

$$\pi/2 \, r \lambda_T \left(1 - \exp{-\frac{2r}{\lambda_T}} \right)$$

where λ_T is the total mean free path for scattering and absorption of the scattered photon, and r is the radius of the scattering cylinder. It is clear that for $r \gg \lambda_T$ the effective area increases only as r, not as r^2. Thus, several polarimeters with radii about equal to λ_T would yield more counts per unit area of scatterer than one large polarimeter.

The advantages of a collimated, solid polarimeter are:

1. light weight, and simple operation;

2. no upper limit on the x-ray energy which can be studied, except that imposed by the gas filled detector (typically about 40 KeV);

3. no need for large structures (telescope and housing) which may create secondary x-rays; and

4. does not require complex systems such as a grazing incidence telescope and cryogenic detector.

IV. INTEGRATION WITH A GRAZING INCIDENCE X-RAY TELESCOPE

Polarization measurements using a grazing incidence x-ray telescope to provide high resolution are likely to become particularly attractive. The detection techniques described in the previous section still apply. However, the current American Science and Engineering plan for a double-reflecting x-ray telescope has a cut-off for x-rays above 6 KeV. Only a liquid-hydrogen polarimeter may be used, since the crossover point between photoelectric absorption and the Compton effect lies above 6 KeV for all other materials. Even using a hydrogen polarimeter only the region between 3 to 6 KeV could be studied. The x-rays arriving in the focal plane of the telescope arrive at angles up to 3° from the axis. This is not sufficient to require any modification of the polarimeter.

The advantages in using a telescope are:

1. discrete sources may be studied with high angular resolution;

2. background may be measured by placing an aperture stop over the small inlet hole to the polarimeter. This would not substantially modify the distribution of matter (telescope and accessories) that produces the x-ray background;

3. a smaller polarimeter may be used for the same count rate obtained from a collimated system.

V.   OBSERVATION TIMES

The observation times for typical sources can be compared between a collimated polarimeter using a solid lithium hydride scatter and a liquid hydrogen scatterer used in conjunction with a grazing incidence telescope. The Crab Nebula has ~ 5 photons/cm^2 sec between 3 and 6 KeV and ~ 10 photons/cm^2 sec greater than 11 KeV. Other sources such as Sco XR-1 have $\sim 10^2$ photons/cm^2 sec between 3 and 6 KeV with ~ 1 photon/cm^2 sec greater than 11 KeV. [5]

A 10 cm^2 collimated solid polarimeter with an intrinsic efficiency of 3% would require about 10 hours to determine the extent of polarization of the Crab Nebula to within 1%. Most other sources would require longer viewing times.

The 25-inch telescope proposed for an advanced stellar ATM mission has a collecting area of ~ 200 cm^2 and a theoretical reflecting efficiency of 50% between 3 and 6 KeV. A liquid hydrogen polarimeter with only 5 cm^2 area could receive $\sim 6 \times 10^4$ photons/sec from Sco XR-1 and determine the extent of polarization to within 1% in several minutes of viewing time. The Crab Nebula would require several hours because of the weaker intensity of this source in this energy range.

It appears that sources which have spectra such that much of the x-radiation is concentrated below 10 KeV may be studied for polarization by telescope techniques. Yet considerable polarization information may be obtained above 10 KeV by the use of small, collimated polarimeters which do not have the cryogenic requirements associated with the liquid hydrogen systems.

VI.   RECOMMENDATIONS

For certain x-ray sources, x-ray polarimetry may provide information on the mechanism of x-ray emission which cannot be obtained unambiguously in any other way. It is unlikely that sufficient counts may be obtained either from a balloon or rocket flight to clearly ascertain the extent of polarization of an x-ray source using a collimated polarimeter. Therefore x-ray polarimeters using solid scatterers (probably Lithium Hydride) should be flown on unmanned satellites where old novae such as the Crab Nebula may be studied for considerable lengths of time. Such sources are likely to have

x-rays produced by synchrotron radiation. A considerable fraction of their x-radiation will lie above 10 KeV and it may be polarized to an observable extent.

If such experiments are successful, then x-ray polarimeters may be useful in grazing incidence telescope operations where man will play a role in maintaining and repairing such systems. The polarization data obtained from an unmanned flight would provide much useful information for the planning of such an experiment for a manned flight.

F. F. Tomblin

1015-FFT-caw

Attachments
References
Figures 1-3

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(2) J. F. Donlan, Space Science Reviews 6, 571 (1967).

(3) J. D. Jackson, Classical Electrodynamics, J. Wiley and
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(5) R. J. Gould, Am. J. of Phys. 3n, 376 (1967).

DIRECTION OF INCIDENT
PHOTON ELECTRIC VECTOR

PROBABILITY
THAT PHOTON
WILL BE
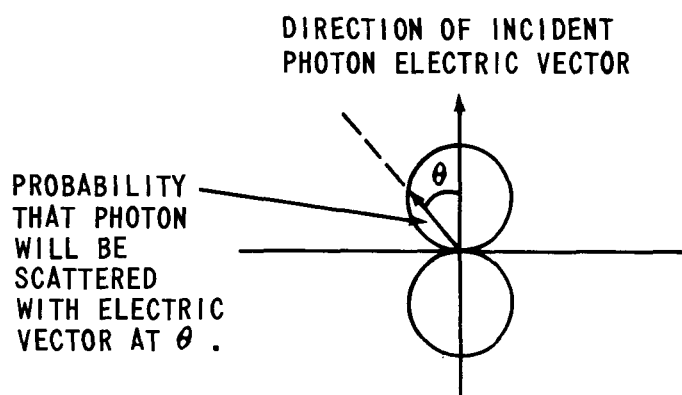SCATTERED
WITH ELECTRIC
VECTOR AT θ .

θ

FIGURE I – PROBABILITY DISTRIBUTION OF ELECTRIC VECTORS COMPTON
SCATTERED AT 90° TO THE INCIDENT PHOTON DIRECTION.
THIS IS A REPRESENTATION OF THE DIFFERENTIAL CROSS
SECTION WITH ANGULAR DEPENDENCE $\frac{d\sigma}{d\Omega} \propto \cos^2 \theta$. THE
INCIDENT PHOTON DIRECTION IS PERPENDICULAR TO THE
PLANE OF THE PAPER; THE PHOTON IS SCATTERED INTO THE
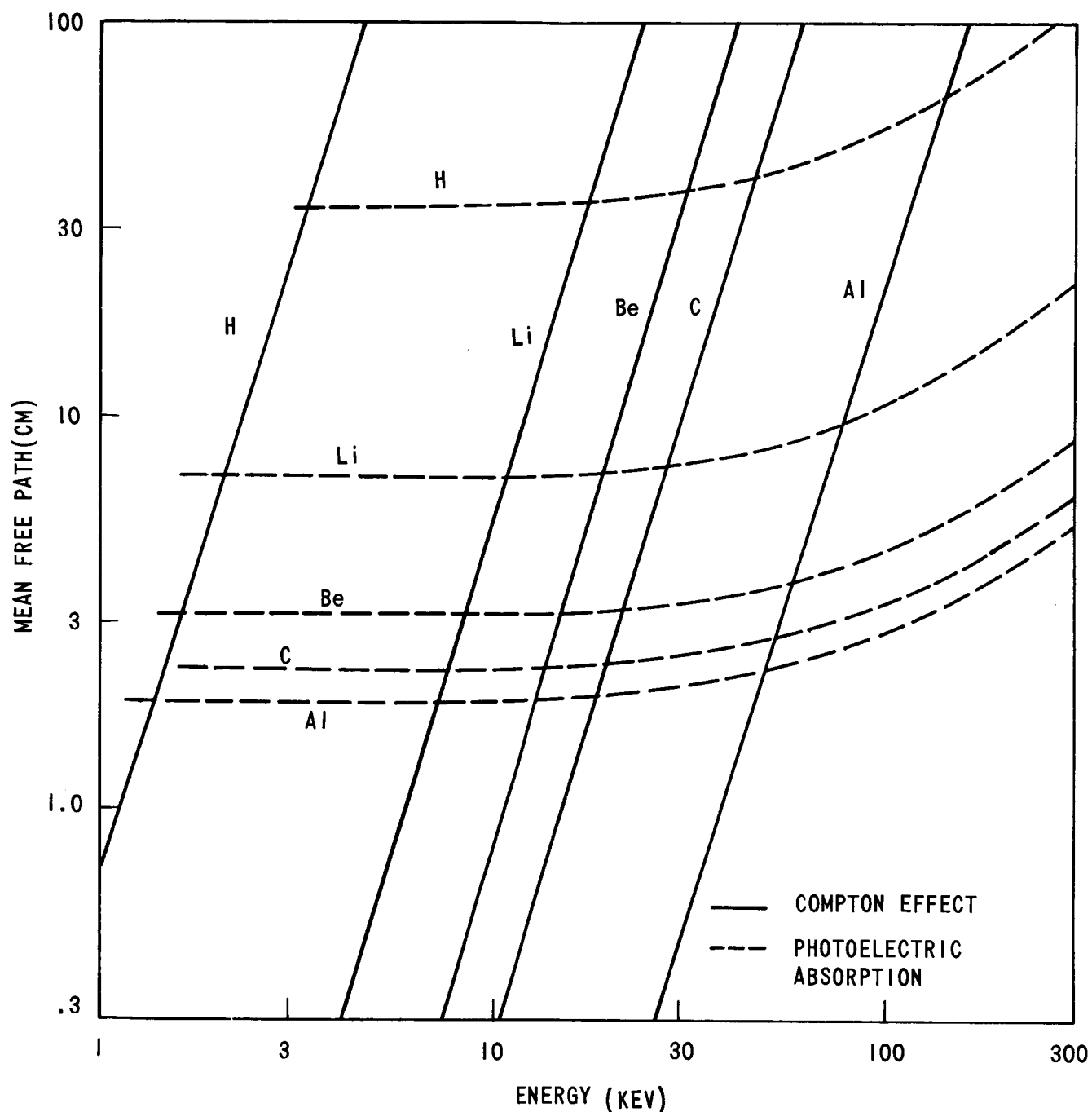PLANE OF THE PAPER, PERPENDICULAR TO ITS ELECTRIC
VECTOR.

FIGURE 2 - THE MEAN FREE PATHES FOR COMPTON SCATTERING
AND PHOTOELECTRIC ABSORPTION FOR VARIOUS
SOLIDS CONSIDERED FOR THE COMPTON POLARIMETER.

CROSS SECTIONAL VIEW

DETECTOR
RING

ANTICOINCEDENCE
DECTOR

COLLIMATORS

COLLIMATORS

COMPTON
SCATTERER

PHOTON
DIRECTION

ANTICOINCIDENCE
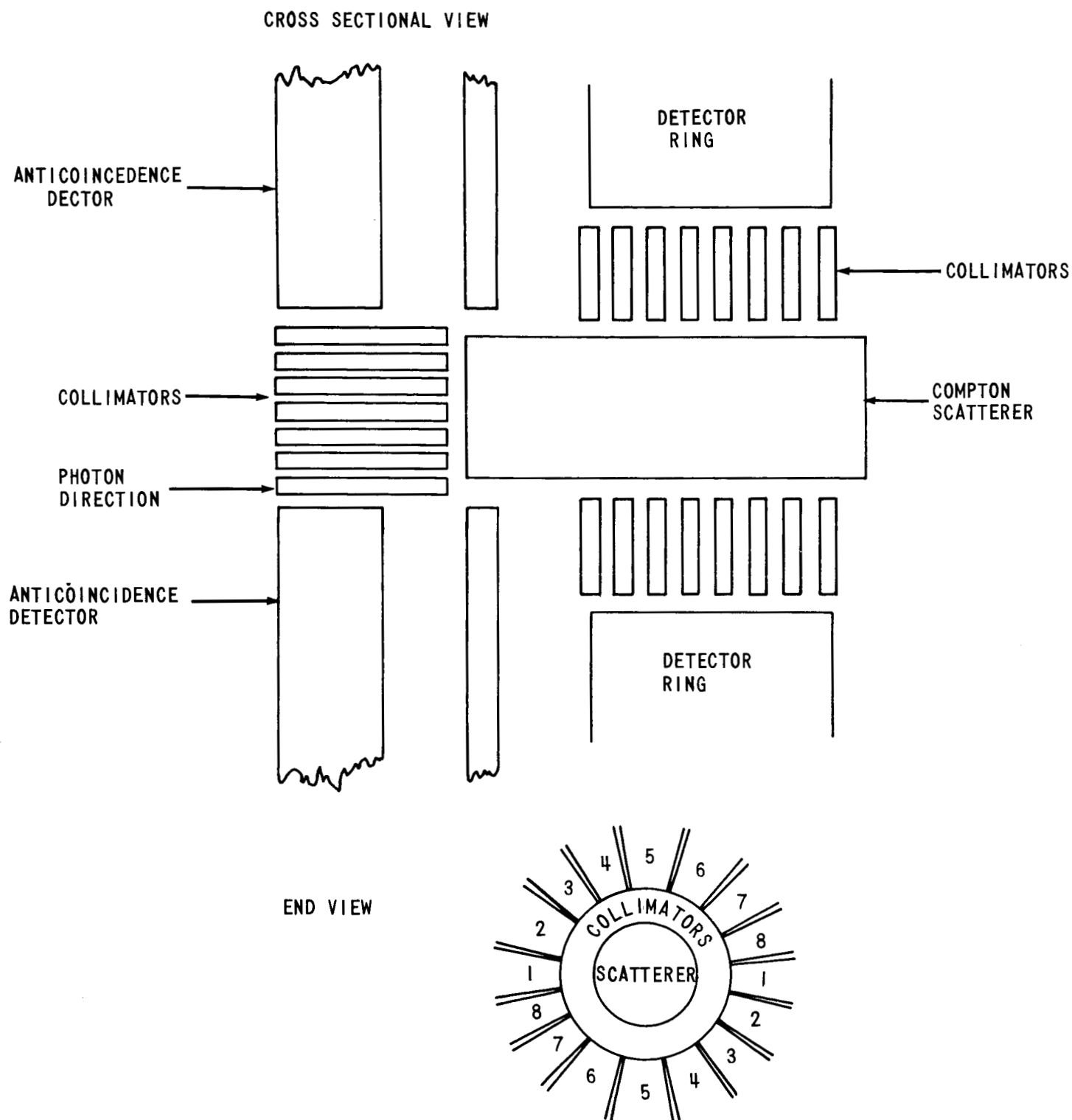DETECTOR

DETECTOR
RING

END VIEW

COLLIMATORS

SCATTERER

FIGURE 3 - CONFIGURATION OF X-RAY POLARIMETER. THE
ANTI-COINCIDENCE DETECTOR WOULD SURROUND
THE ENTIRE EXPERIMENT TO ELIMINATE MOST
COSMIC RAY EFFECTS. DETECTORS WITH SIMILAR
NUMBERS (END VIEW) WILL BE CONNECTED IN
PARALLEL TO THE SAME MEMORY BANK SINCE THE
COUNTS IN DIAMETRICALLY OPPOSED DETECTORS
SHOULD BE IDENTICAL.

BELLCOMM, INC.

Subject: Polarization Measurements on   From: F. F. Tomblin
Stellar X-ray Sources

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